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A STUDY OF HEAVY-HEAVY NUCLEAR REACTIONS

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A STUDY OF HEAVY-HEAVY NUCLEAR REACTIONS

This report includes the progress of research in the study of heavy-heavy nuclear reactions.

As is known, for future long-duration and high altitude missions, the problem of exposure to cosmic rays should be considered rather seriously. One is here talking about ions as heavy as iron and with energies as large as 10^{17} eV. Thus, the cross sections for heavy ions when bombarded on various materials must be determined.

In the attachment (submitted for publication in Physics Letters) is presented a simplified theory for heavy ion scattering which shows good agreement with heavy ion absorption experiments. Theoretical implications on the complete coupled channel reaction equations are discussed.

The Principal Investigator is currently involved in understanding the SPAR program which will obtain range, stopping power, etc. for heavy ions incident on various materials.

HIGH-ENERGY HEAVY ION ABSORPTION CROSS SECTION

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A simplified theory for heavy ion scattering shows good agreement with heavy ion absorption experiments. Theoretical implications on the complete coupled channel reaction equations are discussed.

An optical model for composite particle interaction was derived by Czyż and Maximon [1] using the Glauber formalism [2] for the scattering of two composite particles. Aside from the high-energy implications of the Czyż and Maximon optical model as based on approximate eikonal theory, their optical model limit requires the two-body constituent amplitudes to vanish as the inverse product of the constituent numbers of the projectile and target. This additional condition is not met by any known physical system and especially not by systems of strongly interacting particles [3]. Motivated by these limitations (the high-energy approximation and nonphysical assumptions) of the Glauber based optical model for heavy ion reaction, an exact multiple scattering formalism and effective potential operator

were derived which alleviated both of those assumptions [4]. The result was, however, left in the form of a simplified many-body Lippmann-Schwinger equation for the transition amplitude yet to be solved.

The many-body Lippmann-Schwinger equation of reference 4 can be reduced to a set of equivalent one-body coupled-channel equations by assuming (1) the kinetic energy is large compared to the level spacings of the projectile and target and (2) closure of the internal eigenstates [5]. Although a high-energy approximation has been made, it is generally less restrictive than the high-energy limit of Glauber theory which requires the projectile wavelength to be small compared to the combined projectile-target radius. Since the coupling between the elastic channel amplitude and the remaining excitation channels is kinematically suppressed [5] as q^{2n} where q is momentum transfer and $n \geq 1$, a coherent approximation for the elastic channel amplitude appears adequate near forward scattering. Furthermore since the scattering at high energies is forward peaked, the elastic scattering should in this case be accurately accounted for by a coherent approximation. Making a coherent approximation, these coupled-channel equations may be reduced to a potential scattering problem for the elastic channel and the resulting equation is solvable by standard techniques. An additional advantage of this last step is that the information required for elastic scattering calculations for heavy ion interaction is obtainable from electron scattering data and nucleon-nucleon scattering experiments. Although the approximations made in deriving this optical model are physically plausible, comparison with experimentally determined quantities measured in heavy ion experiments provides the ultimate test of their adequacy.

The coherent-elastic amplitude for heavy ion scattering satisfies the equivalent one-body Schroedinger equation [5]

$$(\nabla^2 + k^2)\,\psi(\underline{x}) = \left(\frac{2mA_pA_T}{N}\right) W(\underline{x})\,\psi(\underline{x}) \tag{1}$$

where $\Psi(\underline{x})$ is the projectile wave function, m the nucleon mass, A_P and A_T are projectile and target constituent numbers, and N is the total number of constituents. The optical potential is given by

$$W(\underline{x}) = A_P A_T \int d^3\underline{z}\; \rho_T(\underline{z}) \int d^3\underline{y}\; \rho_P(\underline{x}+\underline{y}+\underline{z})\, t(k,\underline{y}) \tag{2}$$

where $\rho_P(\underline{y})$ and $\rho_T(\underline{z})$ are the projectile and target single particle densities and $t(k,\underline{y})$ is the two-body transition amplitude.

In the present calculations, the proton single particle densities were extracted from the nuclear charge densities compiled by Hofstadter and Collard [6]. We assume the neutron density to equal the proton density. The two-body scattering amplitudes were appropriately averaged over projectile and target constituents. The spin independent parameters given by Hellwege [7] and the Particle Data Group at Berkeley [8] were used to determine the two-body transition amplitudes. Since the available experimental heavy ion scattering data were obtained at high energies, the eikonal approximation was used to solve equation (1). The total cross section was found using the optical theorem and the reaction cross section is taken as the total cross section minus the total coherent-elastic cross section.

There are three data sets with which comparisons will be made. The first data set is based on measurements by Heckman, Lindstrom, Greiner, and Bieser using counter experiments and an oxygen beam of 2.1 GeV/nucleon. The experimental data in figure 1 is the Heckman et al. data as quoted

by Bowman et al. in an LBL preprint presented at the First High Energy Heavy Ion Summer Study held at Berkeley in July 1973 [9]. The uncertainty in the theoretical results due to uncertainty in the single particle density parameters and the two-body amplitudes is typically 5 percent. The unusually large disagreement (15 percent) for the hydrogen target is believed to be an experimental difficulty since good theoretical agreement with proton absorption experiments in this energy range is generally obtained [10].

The second data set was measured in nuclear emulsion by Medina et al. using ion beams of carbon, nitrogen, and oxygen of energy 2.1 GeV/nucleon [11]. For the purposes of comparison, we have calculated the mean free path for average G.5 emulsion at 60 percent relative humidity [12]. The emulsion density used is then 3.84 g/cm^3 while the actual density varies by about ±3 percent. The emulsion composition used is shown in table 1 where the carbon and oxygen of the gel are taken as equivalent to nitrogen which leads to only a).5 percent error in mean free path. The average emulsion cross section is found from

$$\sigma_E = 0.128(\sigma_{Ag} + \sigma_{Br}) + 0.337\,\sigma_N + 0.408\,\sigma_H \tag{3}$$

and is related to the mean free path by

$$\ell_E(\mathrm{cm}) = 12.660/\sigma_E(\mathrm{mb}) \tag{4}$$

The theoretical mean free path in G.5 emulsion is shown in figure 2 in comparison to the results of Medina et al. Note that the near independence

of mean free path on projectile mass in the boron to oxygen region is well displayed by the Medina et al. data. This behavior is the result of a decrease in nuclear skin thickness with increasing atomic weight for these nuclei [6], (e.g., the rms charge radius for $6 \leq A \leq 14$ is 2.4 ± 0.1 fm).

The third data set is compiled from numerous data obtained by nuclear emulsion measurements with the galactic cosmic rays as an ion source [13-18]. Aside from the problem associated with variability of the composition of the emulsion, the exact properties of the projectile are rarely known placing further limitations on comparisons. Although some efforts have been made to measure energy dependence of the mean free path of different projectile species, the statistical uncertainty associated with such measurements completely masks such variation as indicated for alpha particles in figures 3. The experimental data shown in figure 3 were obtained using the galactic cosmic rays [13,14,16] with the exception of the point near 100 MeV/nucleon obtained by Willoughby [19] at a Berkeley accelerator. As shown in figure 3, the mean free paths are very nearly independent of energy with the largest variation being for protons (20 percent variation) and alpha particles (13 percent). We will use only the energy averaged quantities which have the smallest statistical fluctuation for the present comparisons. The theoretical mean free paths were averaged over the energy spectrum.

$$\varphi(E) = (E + 940)^{-2.5} \tag{5}$$

where E has units MeV/nucleon. The beam composition was divided into the usual charge groups as alpha particles ($Z = 2$), L ($3 \leq Z \leq 5$), M ($6 \leq Z \leq 9$),

LH ($10 \leq Z \leq 19$), H ($10 \leq Z$), and VH ($20 \leq Z$). The nuclear emulsion mean free path for each group was obtained by using the galactic cosmic ray composition as given by Shapiro and Silberberg [20]. The results of cosmic ray measurements for these groups are shown in comparison with the present theoretical results in table 2. As can be seen from table 2, the present theoretical results are consistent with the cosmic ray data with one exception appearing as the first entry of the last column (VH) of table 2.

It appears from the present comparisons that equation (1) is a good approximation to the elastic channel, at least at energies above several hundred MeV/nucleon. In this region the eikonal approximation is entirely adequate and the Glauber formalism [2] is expected to obtain similarly good results. The only advantage of equation (1) over Glauber theory in this energy range is the simplicity of equation (1). At sufficiently low energy, the eikonal approximation (hence, Glauber theory) will become inadequate and the question is: To what energy range does equation (1) apply? An interesting experiment in this respect would be the interaction of light nuclei such as deuterons and alphas in the range below 300 MeV/nucleon with various target nuclei.

It is clear from the present results that the coherent approximation is adequate at high energies implying that coupling to inelastic channels has only minor effects on the total elastic event. The incoherency effects should be observed in the elastic channel only at relatively high momentum transfers. If the higher order couplings of the inelastic channels to the elastic channel are insignificant, then we may conclude that higher order inelastic coupling among the inelastic

channels is negligible also, as a result of the tendency of the high-energy heavy ion events to be inelastic [5]. It is anticipated that a distorted-wave Born approximation would adequately describe most of the inelastic events exclusive of the very important final state interactions.

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Table 1. G.5 emulsion composition used in present calculation

	Percent by number
Ag	12.8
Br	12.8
N	33.7
H	40.8

Table 2. Cosmic ray mean free paths (cm) in G.5 emulsion compared to present calculation.

	α	L	M	LH	H	VH
W.U.-Bristol[a]		17.6±1.9	14.6±1.0		10.4±1.0	
Bristol[b]						9.4±0.4
Bristol[b]				11.4±1.2		8.4±0.8
Waddington[b]				10.1±1.0		8.7±0.6
Chicago[c]		13.4±1.9	13.0±0.9		11.5±1.2	9.2±2.1
Bristol[d]	20.5±2.2	13.4±1.6	12.5±1.0		9.6±0.8	8.1±1.1
Turin[e]		15.6±1.8	13.4±1.0		11.1±1.3	
Theory	21.5±1.3	15.5±0.9	14.3±0.9	11.3±0.7	10.5±0.6	7.7±0.5

a. Ref. 17
b. Ref. 18
c. Ref. 16
d. Ref. 13,14
e. Ref. 15

Figure Captions

Fig. 1. Comparison of the present theory with oxygen ion experiments performed by Heckman et al.

Fig. 2. Comparison of the present theory with nuclear emulsion experiments using ion beams of carbon, nitrogen, and oxygen performed by Medina et al.

Fig. 3. Energy dependence of nuclear emulsion mean free paths for various groups of nuclei. Also shown are experimentally determined alpha particle mean free paths from various authors.

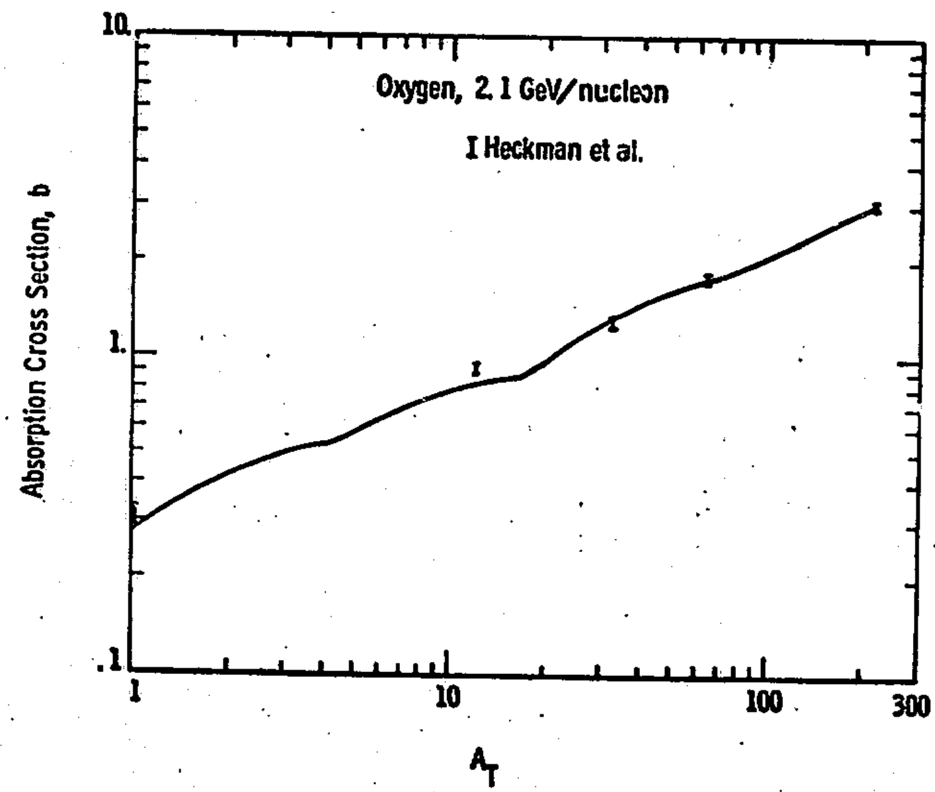

Fig. 1
Wilson-Costner
Heavy Ions

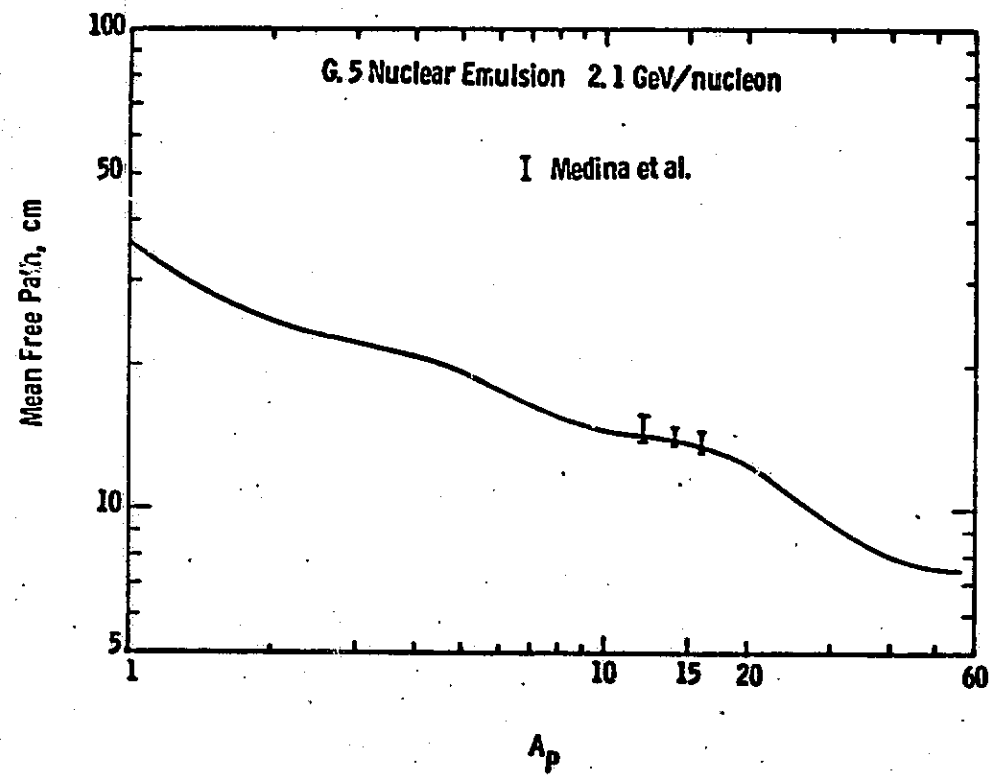

Fig. 2
Wilson-Costner
Heavy Ions

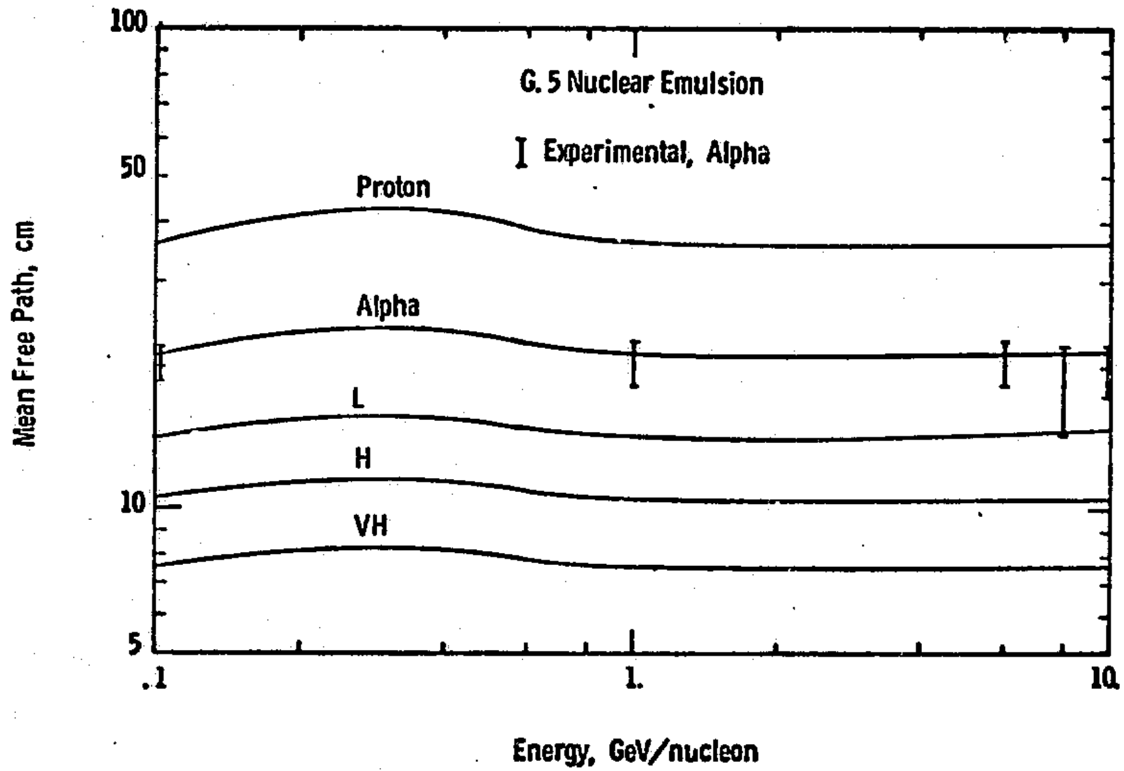

Fig. 3
Wilson-Costner
Heavy Ions